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Volume 2, Issue 1 - October 2013

The New Sciences of Networks & Complexity: A Short Introduction

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Abstract

This paper is the result of two recent e-workshops organized by The World Academy of Art and Science (WAAS), one on the Science of Networks, the other on Complexity. These Sciences have emerged in the last few decades and figure among a large group of 'new' sciences or knowledge acquisitors. They are connected with one another and are very well exposed in the diagram available under the name 'Map of Complexity Science' on Wikipedia. Networks exist in extremely diverse contexts: in the biological world, in social constructions, in urbanism, climate change and many more. The novelty appears in the correlations and the laws (e.g. power laws), which were discovered recently, and indicates a totally different appraisal from what was generally expected to exist. The Science of Complexity is directly related to networks. Networks are an essential part of the complexity phenomenon. Their applications, which are highly diverse, are recommended by several scientists; decision makers and politicians have to make use of this knowledge for better evaluation of the impact of their decisions in increasingly complex societies and as a function of time. The paper mentions a recent report on Complexity in Economics and the Economic Complexity Index.

1. Preamble & Frame

Networks and complexity have been recognized since quite a few decades. In recent years, real breakthroughs have taken place with the help of new mathematical instruments. Other 'new sciences' have emerged, say in about half a century, as illustrated by the comprehensive diagram published in Wikipedia;[1] the diagram comes from a book by Brian Castellani and Frederic Hafferty[2] titled *Sociology and Complexity Science: A New Field of Inquiry (2009),* and is called the *Map of Complexity Science.* It was a helping hand for drafting this paper, and is further highly recommended to be consulted. A multitude of new knowledge 'providers' have shown new ways and insights for exploring entities, ensembles and behavior of groups in very different domains. According to the diagram, quite a number of new sciences have emerged since the mid-20th century: the essential pillars for new ideas are Systems Theory,[3] Cybernetics[4] and Artificial Intelligence; a series of specific approaches emerge from there.

Cybernetics plays a central role in the acquisition of new or additional knowledge. Merriam-Webster defines the term this way:

> *"Cybernetics is the science of communication and control theory that is concerned especially with the comparative study of automatic control systems (as the nervous system and brain and mechanical-electrical communication systems)."*

According to the diagram, the Science of Complexity was preceded and followed directly or in parallel by a series of new methods and approaches such as self-organization/autopoiesis, New Sciences of Networks and Global Network society. Not to forget the importance of the Dynamics of Systems Theory in which Jay Forrester of MIT occupies a major role which led to the publication of *The Limits to Growth* (1972), the first report to the Club of Rome.[5]

> *"The New Sciences are to be understood as complementary to the 'classical' sciences."*

We all agree that our societies evolve to more complex entities; the evolution is expressed by economic globalization, planetary communications – wired and wireless – geopolitical conflicts, and the like. However, the decision processes at the political and societal levels continue to rely on habits and practices from ancient times: the rule of thumb method is still used in decision processes. The linear analysis in decision processes still remains the most used approach in management and governance questions, although we are aware of the complexity of societal situations. Therefore, the new sciences,[6, 7] in particular networks and complexity, provide excellent new methods for analysis and prospective insights. As a matter of fact, we may treat networks as patterns or structures but complexity is an implicit property of such structures.

Focusing on New Sciences looks to be a very promising endeavor, in particular for WAAS. Although the field of these new 'knowledge producers' is extremely broad, it provides new understandings, and establishes specific relationships between actors in many branches of sciences and contributes beyond present assumptions.

The New Sciences are to be understood as complementary to the 'classical' sciences; they 'uncover' new relationships, new laws (of mathematical character), and new characteristics among the parameters. The new sciences enable us to take non-linear relationships within systems into account, which was almost impossible before.

There are several fundamental problems where the applications of the Sciences of Networks & Complexity provide new insights in pure scientific domains, for example in the functioning of metabolisms in micro-organisms; applications in the domain of climate change and eco-biosphere are expected to bring a better understanding on the regional and planetary scale. In the fields of sociology and economics, these problems include new methods which enhance diagnostics that were not available before.

The governance of complex industrialized societies requires a better understanding of their underlying trends and institutional political decision processes. The methods applied so far do not appear to be able to provide appropriate guidelines. New insights into the organization of very large institutions, ministries and businesses, of international governing bodies, and perhaps in the governance of financial world, etc. require approaches which the science of networks and complexity can offer.

For long, scientists have expressed the need for cross-domain analyses, overcoming the exclusive approach of specialized understanding and arriving at an overarching understanding, denominated as a *holistic* methodology. The Western science and culture of the Renaissance have made tremendous progress based on *reductionist* analytical methods. However, these assumptions are frequently insufficient for a deeper understanding of reality. The well-known phrase *'The whole is more than the sum of the parts'* (attributed to Aristotle) is not only correct but now much more practicable than a reductionist approach. With the emergence of the Systems Theory, Complexity Science and related methods, a holistic understanding is at reach.

2. The Science of Networks

Several models of networks[8] have been described over time: *Random Network* known as the Erdös-Rényi Model[9] (1959); *Scale-Free Model* known as the BA Model called after Barabasi & Albert[10, 11] (1999); *Small World Model* known as the Watts-Strogatz algorithm[12] (2008).

It must be stressed that mathematical tools have contributed substantially to analyses of the descriptions, characteristics and properties of networks, thus contributing to an understanding of reality which is yet to be recognized.

2.1 Scale-Free Networks and Power Law[13, 14]

Over the past few years, investigators from a variety of fields have discovered that many networks – from the World Wide Web to a cell's metabolic system to actors in Hollywood – are dominated by a relatively small number of nodes that are connected to many other nodes.

Networks containing such important nodes or hubs tend to be what is called "scale-free" in the sense that a lower number of hubs has higher links and many nodes have less number of links. The surprising discovery was that these networks do not behave in the expected random behavior, which is a generally accepted description of phenomena in physics, resulting frequently in the well-known 'bell' curve coming from a usual statistical distribution, characterized by log-log relationships which form the 'power law'.

It is important that the scale-free networks behave in certain predictable ways: for example, they are remarkably resistant to accidental failures but extremely vulnerable to coordinated attacks.

As an example, counting how many webpages have exactly *k* links showed that the distribution followed a so-called *power law*: the probability that any node is connected to k other nodes is proportional to $1/k^n$. The value of n for incoming links is approximately 2. Power laws are quite different from the bell-shaped distributions that characterize random networks. Specifically, a power law does not have a peak like a bell curve does (Poisson distribution), but is instead described by a continuously decreasing function. When plotted on a log-log scale, a power law is a straight line. In contrast to a 'democratic' distribution of links seen in random networks, *power laws* describe systems in which a few hubs dominate.

2.2 Some Important Properties of Networks

2.2.1 Resilience /Robustness[15]

As humanity becomes increasingly dependent on electricity grids and communication webs, a much-voiced concern arises: Exactly how reliable are these types of networks? The good news is that complex systems can be amazingly resilient against accidental failures. In fact, although hundreds of routers routinely malfunction on the Internet at any moment, the network rarely suffers major disruptions. A similar degree of robustness characterizes living systems: people rarely notice the consequences of thousands of errors in their cells, ranging from mutations to misfolded proteins.

What is the origin of this robustness? Intuition tells us that the breakdown of a substantial number of nodes will result in a network's inevitable fragmentation. This is certainly true for random networks: if a critical fraction of nodes is removed, these systems break into tiny, non-communicating islands.

Yet, simulations of scale-free networks tell us a different story: as many as 80 percent of randomly selected Internet routers can fail and the remaining ones will still form a compact cluster in which there will still be a path between any two nodes.

It is equally difficult to disrupt a cell's protein-interaction network: measurements indicate that even after high levels of random mutations are introduced, the unaffected proteins will continue to work together.

In general, scale-free networks display an amazing **robustness** against accidental failures, a property that is rooted in their inhomogeneous topology. The random removal of nodes will take out the small ones mainly because they are much more plenty than hubs. And the elimination of small nodes will not disrupt the network topology significantly, because they contain few links compared with the hubs, which connect to nearly everything. But a reliance on hubs has a serious drawback: vulnerability to attacks.

In a series of simulations, it was found that the removal of just a few key hubs from the Internet splintered the system into tiny groups of hopelessly isolated routers. Similarly, knockout experiments in yeast have shown that the removal of the more highly connected proteins has a significantly greater chance of killing the organism than the deletion of other nodes. These hubs are crucial; if mutations make them dysfunctional, the cell will most likely die.

2.2.2 Strengths and Weaknesses

A reliance on hubs can be advantageous or not depending on the system.

First, one has to note that resistance to *random* breakdown is good news for both the Internet and the cell. In addition, the cell's reliance on hubs provides pharmaceutical researchers with new strategies for selecting drug targets, potentially leading to cures that would kill only harmful cells or bacteria by selectively targeting their hubs, while leaving healthy tissues unaffected.

Second, the ability of a small group of well-informed hackers to crash the entire communications infrastructure by targeting its hubs is a major reason for concern.

> *"How can systems as fundamentally different as the cell and the Internet have the same architecture and obey the same laws?"*

2.3 Some Examples of Applications

Over the past several years, researchers have uncovered scale-free structures in a stunning range of systems which include

- the **World Wide Web**;
- some **social networks**. A network of sexual relationships among people (from a research in Sweden) followed a power law: although most individuals had only a few sexual partners during their lifetime, a few (the hubs) had hundreds;
- the network of people connected by **e-mail**;
- the network of **scientific papers**, connected by citations, follows a power law: collaborations among scientists in several disciplines, including physicians and computer scientists;
- **business networks**; a study on the formation of alliance networks in the U.S. biotechnology industry discovered definite hubs;
- the network of **actors in Hollywood**: popularized by the game Six Degrees of Kevin Bacon, in which players try to connect actors via the movies in which they have appeared together. A quantitative analysis of that network showed that it, too, is dominated by hubs;
- **biological realm**: in the cellular metabolic networks of 43 different organisms from all three domains of life, including *Archaeoglobus fulgidus* (an archae-bacterium), *Escherichia coli* (a eubacterium) and *Caenorhabditis elegans* (a eukaryote), it was found that most molecules participate in just one or two reactions, but a few (the hubs), such as water and adenosine triphosphate, play a role in most of them;
- **protein-interaction** network of cells. In such a network, two proteins are "connected" if they are known to interact with each other. Investigating **Baker's yeast**, one of the simplest eukaryotic (nucleus-containing) cells, with thousands of proteins, a scale-free topology was discovered: although most proteins interact with only one or two others, a few are able to attach themselves physically to a huge number; a similar result was found in the **protein-interaction** network of an organism that is very different from yeast, a **simple bacterium** called *Helicobacter pylori*.

Indeed, the more scientists studied networks, the more scale-free structures were discovered. These findings raised an important question: How can systems as fundamentally different as the cell and the Internet have the same architecture and obey the same laws? Not only are these various networks scale-free, they also share an intriguing property: for reasons not yet known, the value of n in the k^n term of the power law tends to fall between 2 and 3.

A compelling question arises: How many hubs are essential? Recent research suggests that, generally speaking, the simultaneous elimination of as few as 5 to 15% of all hubs can crash a system.

3. The Science of Complexity

3.1 General Remarks

The focus lies on the innovative character of this new science, in terms of **scientific development**: mathematical, biological, as well as in terms of societal behavior, in particular in **sociology** but also in **economics**. Will industrial societies evolve to a new pattern of evolution/development under the influence of these new network facilities created by entirely new technologies? Relationship between individuals, or inter-subjectivity, will depend on the availability and accessibility of network and complexity methodologies. Therefore, uncovering new types of relationships enables more sustainable prospective scenarios on how our industrial societies will or could look like by the mid-21st century.

Important issues to be examined are democratic processes through the existence or 'spontaneous' emergence of networks. This new phenomenon becomes an important parameter in electoral campaigns, in major political processes as overthrowal of leaders, local and community issues. This very interesting domain is open for debate and reflection.

The state of knowledge about networking and complexity will play an increasing role in understanding the organization and functions of societies. Some most recent events and tendencies, in a large variety of domains, indicate the richness of applicability of these sciences: analysis and search for remediation of the worldwide financial crises; underlying political channels and possible solutions regarding the events in the Middle East; nature and size of social developments in nations with emerging economies; health research and disease dissemination; impact of diminishing bio-diversity on human society and on a planetary scale etc.

The issues which have not yet found appropriate and durable (sustainable) answers will most likely find substantial progress with the application of these new sciences. The understanding of such phenomena requires other type of approaches – more holistic than reductionist – necessary for improved diagnosis and resulting in a better understanding and increased acceptance of proposed solutions.

In the case of world problems, the search for appropriate solutions by international organizations within the present political frame shows quite clearly that progress can only be made by other approaches than the one used until now, based on scientific analysis and understanding, in which these new sciences will play a substantial role.

3.2 The Science of Complexity: Definitions, Properties & Tools

3.2.1 Definitions

Defining complexity remains not an easy task. Some definitions below are taken from publications and depend strongly on the viewpoint of the authors.

From Melanie Mitchell (2009):[16]

> *"Complexity is a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution."*

From Roger Lewin (1993):[17]

> *"Complexity science offers a way of going beyond the limits of reductionism, because it understands that much of the world is not machine-like and comprehensible through a cataloging of its parts; but consists instead mostly organic and holistic systems that are difficult to comprehend by traditional scientific analysis."*

From the OECD Global Science Forum *Applications of Complexity Science for Public Policy: New Tools for Finding Unanticipated Consequences and Unrealized Opportunities* (2009):[18]

> *"Government officials and other decision makers increasingly encounter a daunting class of problems that involve systems composed of very large numbers of diverse interacting parts. These systems are prone to surprising, large-scale, seemingly uncontrollable, behaviors. These traits are the hallmarks of what scientists call complex systems.*
>
> *An exciting, interdisciplinary field called complexity science has emerged and evolved over the past several decades, devoted to understanding, predicting, and influencing the behaviors of complex systems. The field deals with issues that science has previously had difficulty addressing (and that are particularly common in human systems) such as: non-linearities and discontinuities; aggregate macroscopic patterns rather than causal microscopic events; probabilistic rather than deterministic outcomes and predictions; change rather than stasis."*

3.2.2 Some Properties

The promise of complexity science for policy applications is, at its core, the hope that science can help anticipate and understand the key patterns in complex systems that involve or concern humans, thus enabling wiser decisions about policy interventions.

Some important characteristics of complex systems are:

- ***Adaptability:*** independent constituents interact changing their behaviors in reaction to those of others, and adapting to a changing environment;
- ***Emergence:*** novel pattern that arises at the system level not predicted by fundamental properties of the system's constituents;

- ***Self-organization:*** a system that operates through many mutually adapting constituents where no entity designs it or directly controls it;
- ***Attractors:*** some complex systems spontaneously and consistently revert to recognizable dynamic states known as attractors. While they might theoretically be capable of exhibiting a huge variety of states, in fact they mostly exhibit the constrained attractor states;
- ***Self-organized Criticality:*** a complex system may possess a self-organizing attractor state that has an inherent potential for abrupt transitions of a wide range of intensities. For a system that is in a self-organized critical state, the magnitude of the next transition is unpredictable, but the long-term probability distribution of event magnitudes is a regularly known distribution (a "power law");
- ***Chaos:*** chaotic behavior is characterized by extreme sensitivity to initial conditions;
- ***Non-linearity:*** non-linear relationships require sophisticated algorithms, and are sometimes probabilistic in nature. Small changes might have large effects, large changes could have little or no effects;
- ***Phase Transitions:*** system behavior changes suddenly and dramatically (and, often, irreversibly) because a "tipping point", or phase transition point, is reached. Phase transitions are common in nature: boiling and freezing of liquids, the onset of superconductivity in some materials when their temperature decreases beyond a fixed value;
- ***Power Laws:*** probabilistic distribution characterized by a slowly decreasing function (log-log), different from the 'familiar' bell-shaped curve.

3.2.3 Tools and Techniques for Complexity Science

Some of the most important complexity tools being used in public policy domains at this time are:

- ***Agent-based or Multi-agent Models:*** in computerized, agent-based simulations, a synthetic virtual "world" is populated by artificial agents who could be individuals, families, organizations, etc. The agents interact adaptively with each other and also change with the overall conditions in the environment;
- ***Network Analyses***: a common feature of many complex systems is that they are best represented by networks, which have defined structural features and follow specific dynamic laws. Scientists seek to identify configurations that are especially stable (or particularly fragile); some network patterns have been identified as predictors of catastrophic failures in real-life networks: electricity-distribution or communication infrastructures.

Additional complexity-related techniques deserve a special mention, although their use is not unique to complexity science: Data Mining, Scenario Modeling, Sensitivity Analysis, Dynamical Systems Modeling.

3.3 Possible Applications in the Public Policy Domain

Several examples of application domains have been explored, e.g.: epidemiology & contagion; traffic, identification of terrorist associations. Of more general interest is climate change, in particular the social and human aspects – connection between economy, finance, energy, industry, agriculture and the natural world. These new degrees of sophistication can only be achieved using complexity science.

Complexity science techniques can be useful in identifying dangerous tipping points in the human-earth system, which can occur independently of purely geophysical transitions. Perhaps, the most likely disruption of this type involves the management of water resources. Drought and water stresses occur regularly across large sections of Europe and the developing world. There are indications that a tipping point may be near, leading to massive long-term water shortages.

3.4 A Recent Topic: Economic Complexity[19]

The recently published The Atlas of Economic Complexity and the Index (ECI) defined in that publication have largely inspired what follows.

Gross Domestic Product (GDP) is the most used indicator to measure the level of economic activity and its evolution in time in terms of economic growth. GDP per capita is used to express the average wealth of the population of a country. However, GDP falls short when it comes to evaluating the well-being of a society.

Many attempts have been undertaken to improve or find better indices to express real progress in well being. In the frame of the Science of Complexity, an interesting approach has been proposed, rather recently, with the creation of the Economic Complexity Indicator (ECI), which focuses on the structure of the economy of a country and enables the diagnosis of its further development or progress, essentially based on the amount of knowledge available in a society for producing goods and services.

In a way ECI shows substantial progress in the evaluation of the economy of a country compared to what the GDP does. The many attempts for elaborating a 'new' economic system cannot oversee this innovative approach in using new sciences such as Networks and Complexity.

3.4.1 What is Economic Complexity?[20]

The complexity of an economy is related to the multiplicity of useful knowledge embedded in it. For a complex society to exist, and to sustain itself, people who know about design, marketing, finance, technology, human resource management, operations and trade laws, must be able to interact and combine their knowledge to make products. These same products cannot be made in societies that are missing parts of this capability set. Economic complexity, therefore, is expressed in the composition of a country's productive output and reflects the structures that emerge to hold and to combine knowledge.

Knowledge can only be accumulated, transferred and preserved if it is embedded in networks of individuals and organizations that put this knowledge into productive use.

Knowledge that is not used, at least as used in this economic context, however, is also not transferred, and will disappear once the individuals and organizations that have it retire or die.

Complex economies are those that can weave vast quantities of relevant knowledge together, across large networks of people, to generate a diverse mix of knowledge-intensive products. Simpler economies, in contrast, have a narrow base of productive knowledge and produce fewer and simpler products, which require smaller webs of interaction. Because individuals are limited in what they know, the only way societies can expand their knowledge base is by facilitating the interaction of individuals in increasingly complex webs of organizations and markets. Increased economic complexity is necessary for a society to be able to hold and use a larger amount of productive knowledge, and we can measure it from the mix of products that countries are able to make.

3.4.2 The Economic Complexity Index (ECI) & the Product Complexity Index (PCI)

First, the amount of embedded knowledge that a country has, is expressed in its productive *diversity*, or the number of distinct products that it makes. Second, products that demand large volumes of knowledge are feasible only in the few places where all the requisite knowledge is available. We define *ubiquity* as the number of countries that make a product. Using this terminology, we can observe that complex products – those that are based on much knowledge – are less ubiquitous. The ubiquity of a product, therefore, reveals information about the volume of knowledge that is required for its production. Hence, the amount of knowledge that a country has is expressed in the diversity and ubiquity of the products that it makes.

Economic Complexity Index (ECI) refers to countries. The corresponding measure for products gives us the Product Complexity Index (PCI). The mathematical approach exploits the combination of these indices as well as the diversity and ubiquity to create measures that approximate the amount of productive knowledge held in each of these countries.

In short, economic complexity matters because it helps explain differences in the level of income of countries, and more importantly, because it predicts future economic growth. Economic complexity may not be simple to accomplish, but the countries that do achieve it, tend to reap important rewards.

4. Complexity Science: New ways of Thinking for Policymakers
(see OECD Report)[21]

The suggested new ways of thinking focus their attention on dynamic connections and evolution, not just on designing and building fixed institutions, laws, regulations and other traditional policy instruments:

– ***Predictability:*** the science of complex systems focuses on identifying and analyzing trends and probabilities, rather than seeking to predict specific events. It will be challenging, though necessary, for policymakers and scientists alike to move beyond strict determinism if they wish to effectively engage in decision making under conditions of uncertainty and complexity.

– ***Control:*** control is generally made possible by identifying cause-and-effect chains and then manipulating the causes. But cause and effect in complex systems are distributed, intermingled and not directly controllable. Complexity science offers many insights into finding and exploiting desirable attractors; identifying and avoiding dangerous tipping points; and recognizing when a system is in a critical self-organizing state.

– ***Explanation:*** analyses done using complexity science methods, insights about the underlying mechanisms that lead to complex behavior are revealed. Although deterministic quantitative prediction is not generally achieved, the elucidation of the reasons for complex behavior is often more important for comprehending what might otherwise be puzzling real-world events.

– ***Changing the Mindset:*** *understanding the basic ideas of complexity of the world together with unpredictability. One should not forget that Albert Einstein has warned: "Not everything that counts can be counted, and not everything that can be counted counts".*

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